Greatly Enhanced Deep Space Mission Data Return Using Very Large DSN Arrays

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Abstract—The Deep Space Network (DSN) can enable greatly enhanced mission data return from deep space missions by implementing very large arrays of relatively small antennas for signal reception. At the same time, the cost per bit of science data return can be reduced by two orders of magnitude compared to today. The vision is to have arrays at each of the three DSN longitudes with aperture and performance equivalent to 100 70-m antennas, within approximately 20 years. Using Ka-band (32 GHz), this would enable data rates 400 to 500 times that achievable by current 70-m antennas using X-band (8 GHz). Alternately, the data rates now achieved at typical Mars distance could be achieved at Pluto. The impact on mapping missions is tremendous. It will be possible for a single mission to map an entire planet, compared to the few percent of the surface that can be mapped by today's missions. Hyper-spectral imaging and high-definition television are also enabled. The baseline system design calls for approximately 3600 antennas, each of 12-m diameter, at each longitude. The antennas would be located at approximately eight widely separated sites at each longitude. This provides weather diversity for Ka-band reception, enabling very high system availability. The site diversity also enables the array to provide the delta-differenced one-way range (delta DOR) data type, which is becoming increasingly important to deep space missions.

TABLE OF CONTENTS

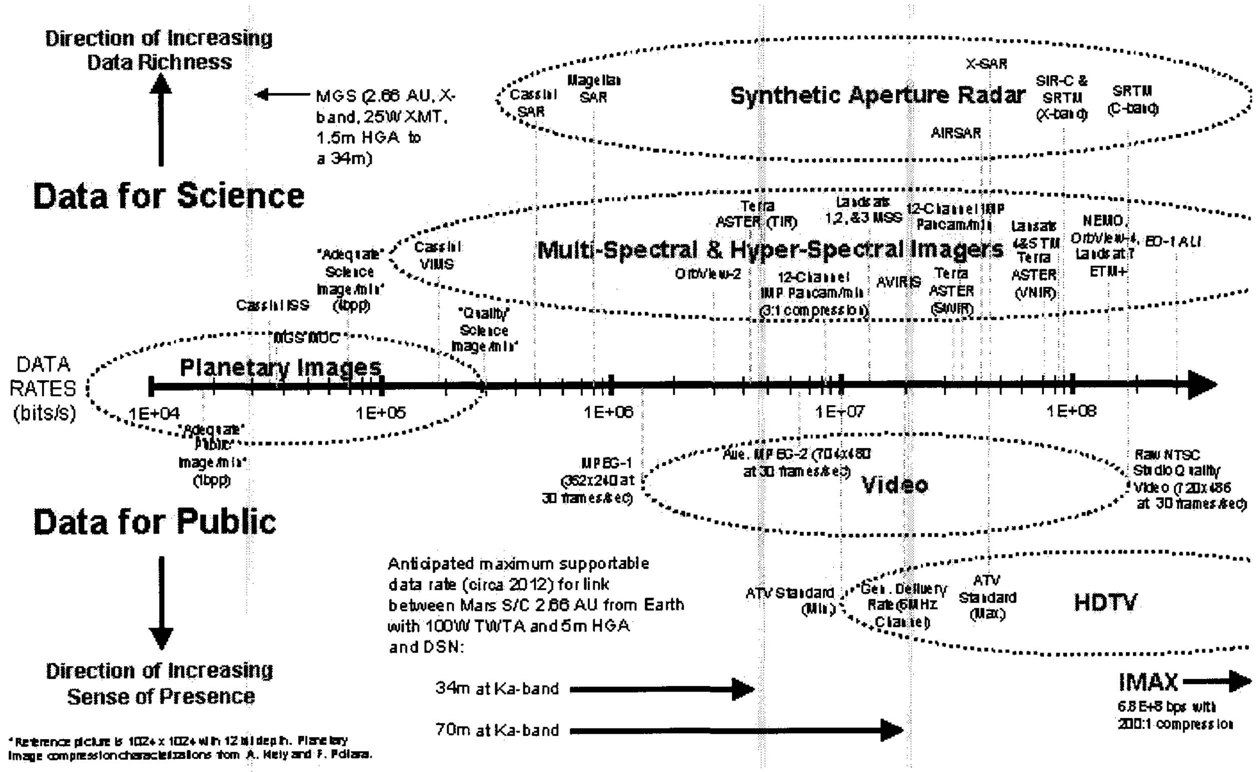
1. INTRODUCTION

The purpose of the proposed DSN Array System is to greatly increase the reception capability of the DSN, thereby enabling greatly increased science data return from missions similar to today's missions, and enabling future missions to meet the anticipated data return discussed in Section 2. The specific goal is to achieve 100 to 500 times increase in DSN signal reception capability at an affordable cost, by 2020.

In addition to enabling increased data return, the Array System could:

1. Enable reduction in spacecraft telecom system mass and power, thus enabling new mission concepts and cost savings.
2. Reduce the cost per bit of science data by two orders of magnitude.
3. Enable high-rate communications from spacecraft well outside of the solar system.

The current status of the Array System is that development is beginning of an Operational Prototype Array System. Some goals are to complete this system by 2008, and to achieve a total array aperture equivalent to 2.8 70-m antennas.



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2. Mission Data Return Needs

An extensive investigation of the future needs for DSN downlink capability was done recently by Abraham [1]. Predicting needs beyond 2010 involved benchmarking DSN-supportable downlink rates for various future mission scenarios relative to Earth-based remote sensing data rate requirements. Two of these benchmarking scenarios from [1] are provided below for purposes of illustration.

Figure 1 shows, relative to a Mars Global Surveyor (MGS) benchmark, a future Mars orbiter/relay scenario in which the spacecraft is using a powerful 100-watt Ka-band transmitter and a huge, deployable 5-m high-gain antenna to downlink its data to DSN 34-m and 70-m assets. Note that such spacecraft telecom equipment does not currently exist, nor does 70-m, Ka-band capability. Despite the huge increase in data rates these assumptions support relative to MGS, the 70-m performance still falls roughly an order-of-magnitude short of the data rates we would like to be able to support at Mars – data rates needed to provide synthetic aperture radar (SAR) and hyper-spectral imagery investigations of the same fidelity as that already being conducted at Earth.

Figure 1. MGS Relative to Mars Orbiter Relay Scenario Circa 2012 (Maximum Supportable Rates at 2.66 AU with RF Flight Hardware Improvements and Ka-band Ground Improvements)

Figure 2 shows how this data rate shortfall becomes more pronounced at more distant targets, in this case at Titan – a likely post-Cassini mission candidate due to the vast quantities of organic molecules present on its surface and in its atmosphere. Again, the scenario assumes a powerful 100-watt Ka-band transmitter and a huge, deployable 5-m high-gain antenna – Ka-band capabilities and telecom equipment that do not currently exist. Note that the 70-m performance now falls roughly two orders-of-magnitude short of the data rates needed to support detailed interferometric SAR measurements and *in situ* hyper-spectral imagery.

3. SYSTEM DESCRIPTION

A high-level pictorial diagram of the Array System is shown if Figure 3
. A large number of relatively small antennas are approximately equally distributed at approximately eight sites on each of three continents, i.e., at three longitudes. The baseline design calls for 3600 12-m diameter antennas at each longitude. This yields a total aperture at each longitude slightly greater than that of 100 70-m antennas.

At each longitude, the antennas are distributed approximately equally at approximately eight sites. The sites are located far enough from each other to provide weather diversity for Ka-band. The sites are spread out both North-South and East-West to provide good baseline geometry for acquisition of the Delta-Differential One-Way Range (Delta-DOR) data type.

Each array site has the antennas and associated equipment, a site signal processing facility,

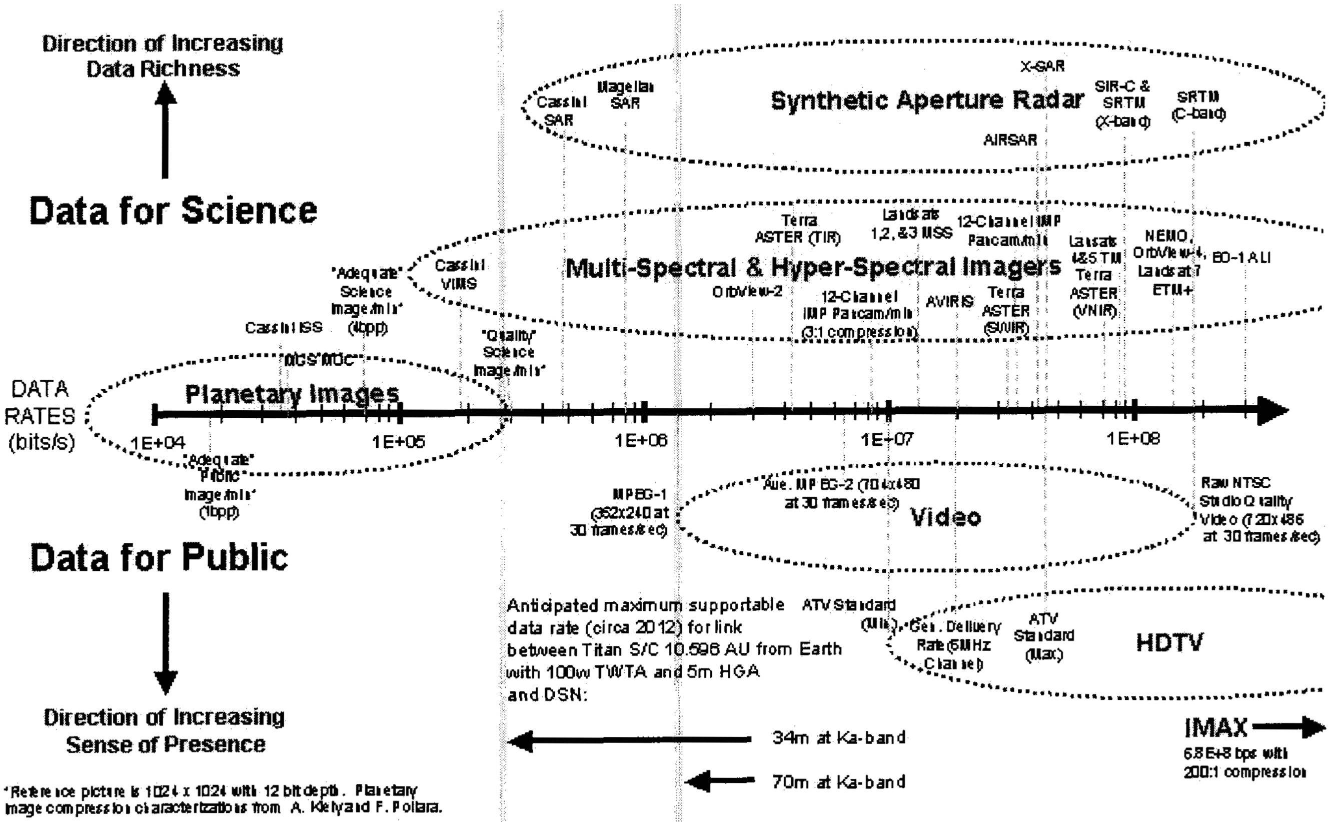

Figure 2. Titan Orbiter Relay Scenario Circa 2012. (Maximum Supportable Rates at 10.6 AU with RF Flight Hardware Improvements and Ka-band Ground Improvements)

communications between the antennas and the signal processing facility, and facilities such as roads, fences and security systems.

System External Interfaces

The main external interfaces to the Array System are:

- Microwave signals from the targets
- Control from other DSN systems at the Deep Space Communications Complexes (DSCCs)
- Array output signals to other DSN systems
- Monitor signals output to other DSN systems
- Frequency and timing signals from the DSN Frequency and Timing System
- Power, water and other facilities

System Composition

The Array System is composed of six subsystems: Antenna and Microwave, Signal Processing, Monitor and Control, Frequency and Timing, Ground Communications, and Facilities.

Antenna and Microwave Subsystem—The purpose of the Antenna and Microwave Subsystem is to receive the signal energy from the targets, and perform all functions necessary to amplify the signals and convert them to a form suitable for interface to the Ground Communications Subsystem. The current plan is for the antennas to be 12-m diameter, fully steerable, shaped paraboloids. The antenna dishes are planned to be one-piece of aluminum, shaped by a hydroforming process, although alternate

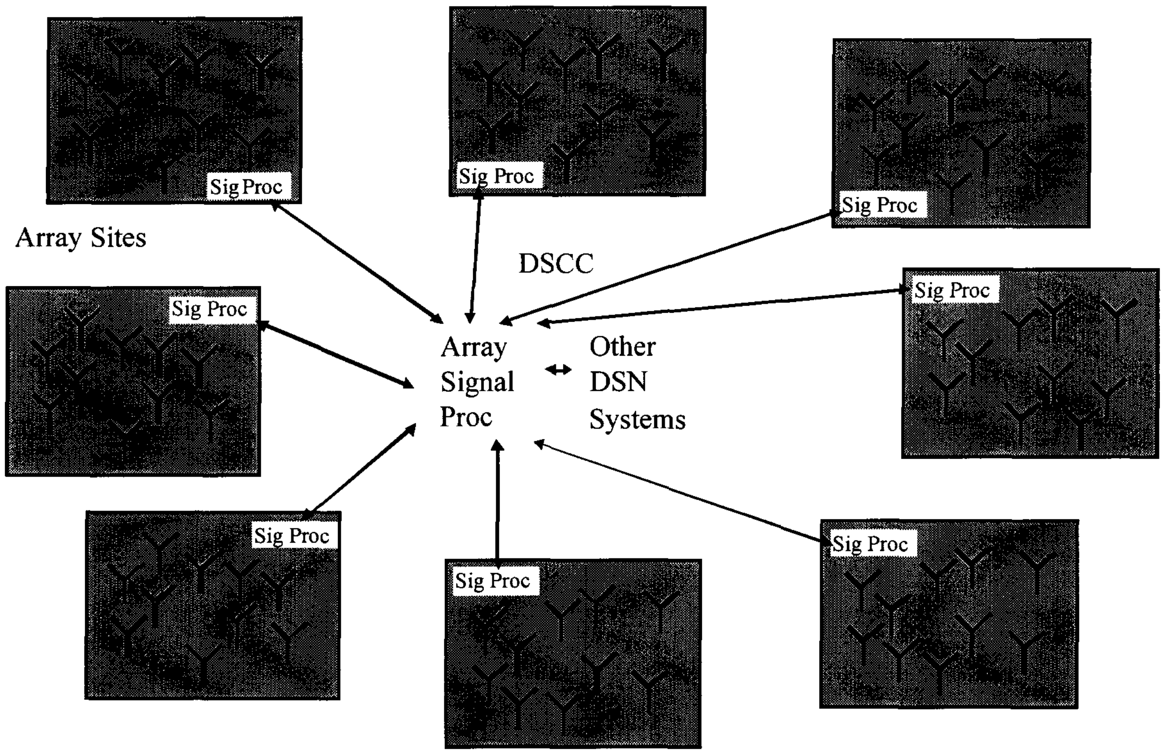

Figure 3. Pictorial Diagram of Array System

approaches are under investigation. There is a significant challenge in achieving an antenna, support structure, pedestal and pointing system with good Ka-band performance. If this cannot be achieved with 12-m antennas at an appropriate cost, smaller antennas may be used.

For each antenna, the Antenna and Microwave Subsystem has dual X- and Ka-band feeds; dual polarization, cryogenic, solid-state, low-noise amplifiers; Ka-band down converters; and antenna pointing equipment.

Signal Processing Subsystem—The purpose of the Signal Processing Subsystem is to perform all processing on the signals from each antenna that is necessary to combine these signals and output them to the other DSN systems in a form that these output signals look very much as if they had each been the signal from one large DSN antenna.

The Signal Processing Subsystem has elements at each array site and at the DSCC at each longitude. At each site, the signal processing subsystem aligns the received signals in time delay and phase, combines the signals, and outputs the combined signals to the Ground Communications Subsystem for transfer to the DSCC. At the DSCC, the Signal Processing Subsystem aligns the signals from each site, combines them, and outputs them to other DSN systems.

Monitor and Control Subsystem—The Monitor and Control Subsystem accepts control inputs from the monitor and control elements of the DSN, controls all other subsystems of the Array System, accepts monitor data from these subsystems, and provides monitor data to the DSN monitor and control. The Monitor and Control Subsystem also inter acts with operations personnel.

This subsystem divides the array system into subarrays, assigns specific antennas to each subarray, and controls the reassignment of antennas in real time, during the tracks. This is done based upon information provided in advance by the DSN monitor and control, but also takes into account real time control, operator inputs, the status of each array antenna, weather and weather forecasts, and the actual performance of each subarray and each element of each subarray. To the extent possible, each target must be supported with the required G/T or with a predetermined number of antennas. There may be other constraints, such as providing geometry for Delta-DOR.

Frequency and Timing Subsystem—The Array Frequency and Timing Subsystem accepts inputs from the DSN Frequency and Timing System, provides locally generated references as required, and provides all frequency and timing references needed by all other array subsystems. It provides monitor data to the Monitor and Control Subsystem.

Ground Communication Subsystem—This subsystem provides all communications services between the antennas and the site signal processing facility, and between the array sites and the DSCCs. There are two challenging requirements. First, tens of Gb/s data rates must be provided from the sites to the DSCCs. Second, high stability analog links must be provided for the frequency references, and for the wideband RF signals from the antennas to the site signal processing facilities.

Facilities Subsystem—This subsystem provides all of the normal facilities, including roads, signal routing ditches, power, water, buildings, bases for the antennas, fences, landscaping, security and fire protection. Facilities will be a significant element of the system cost, both in the development and operations phases.

Personnel—Operations and maintenance personnel are key elements of the Array System.

Array System Signal Processing and Operations Concept
For descriptions of the planned Array System signal processing and operations concept, please see reference [1].

4. PERFORMANCE

In this section we estimate the performance of the array system. First the capability of the array at one longitude is compared to the capability of one 70-m antenna. This gives a comparison of the peak data rates for tracking one spacecraft. Then we compare the overall capacity of the DSN with the Array System to the overall capacity today. This gives a comparison of the total amount of data that can be returned from all missions supported by the network.

Performance Compared to One 70-m Antenna

The simplest basis for comparison of downlink performance is the ratio of antenna gain to system temperature, G/T.

Gain depends mainly on antenna area and received frequency, but also depends importantly on antenna efficiency, which is the ratio of effective area to actual area. The efficiency reflects the various losses from an ideal antenna. System temperature depends on the noise temperature of the low noise amplifier (LNA), and also on various losses in the antenna and microwave elements.

The Ka-band LNA noise temperature for the array antennas is expected to be a few Kelvins higher that those of the 70-m and 34-m antennas, because the cryogenics and the LNAs themselves must be much lower cost than for the large antennas. The other effects, however, are expected to favor the array antennas. The array antennas will be designed for performance up to 43 GHz, and will have a very good surface at 32 GHz. Because of their small size and lightweight, they will have very little gravitational distortion. They will have tapered illumination for high efficiency, and low blockage from the subreflector. The feed will be cryogenically cooled. Other microwave losses will also be small, especially compared to the losses in the beam waveguides of the 34-m antennas.

Our best estimate as of this writing is that the Ka-band performance of each array antenna will be the same as the currently committed performance of the 34-m BWG antennas, scaled by the antenna areas. The required G/T of the BWG antennas at all frequencies from 31800 is at least 64.5 dB at all elevations from 30 degrees to 60 degrees, and at least 63.8 dB at all elevations from 10 degrees to 80 degrees, assuming operation in a vacuum. Scaling by area, the corresponding G/Ts for a 12-m array antenna are estimated to be 55.5 dB and 54.8 dB.

Another way to look at performance is to observe that 36 12-m antennas have an area equal to 1.058 times that of one 70-m antenna. The G/T would be 0.24 dB better. Allowing for typical combining losses, and to the accuracy of our current estimates, the performance of one 70-m antenna can be achieved by arraying 36 12-m antennas.

The goal is to implement 3600 12-m antennas at each of the three DSN longitudes. This number of antennas was chosen so that the peak G/T capability of the Array System will be 100 times that of one 70-m antenna, with all antennas operating at Ka-band.

Weather Diversity. Weather is a significant problem at Ka-band. Moisture in the atmosphere causes significant attenuation and increase in system temperature. In planning link budgets for telemetry reception, missions count on the G/T that will be exceeded with some probability. At X-band, the probability distribution of G/T has a fairly small standard deviation, so that the G/T that is exceeded 95 to 99 percent of the time, is not much less than the average G/T. Thus missions typically operate at these points, or with 95 to 99 percent weather margin. At Ka-band, however, the standard deviation of G/T is much higher than at X-band, and the tails of the probability distribution are much worse than for a normal distribution. This renders it impractical to operate with 95 to 99 percent weather margin. Typical operation is at 90 percent weather margin, which results in a situation with high data return volume, but with significant data losses.

The Array System will largely overcome this Ka-band data outage problem. A simple way to operate the Array System would be to allocate to a mission an equal number of antennas at each of the array sites. The signals from the antennas at the various sites are combined in one sub array. Making the simplifying assumption that the weather is statistically independent between the sites, the standard deviation of G/T is smaller by a factor of the square root of the number of sites, compared to using the same total number of antennas at one site. Also, the probability distribution of G/T tends towards the normal distribution. This operations concept will enable Ka-band operation with 99 percent or even higher weather margin, while operating fairly close to the average G/T.

Preliminary analysis indicates that this benefit of site diversity will be equivalent to increasing the average G/T for one antenna or one site by more than 25 percent. Thus, taking the site diversity into account, the full Array System will have approximately 125 times the capability of one 70-m, Ka-band antenna.

Other Features of Site Diversity. Besides weather diversity, site diversity provides other advantages. Two of these follow. First, the diversity increases the availability of the system and reduced the required reliability of system elements. If a whole site fails, or if the communications link between the site and the system central signal processing fails, this is no worse than having heavy rain at the site. All but one of the sites are still available, so that there is a relatively minor decrease in signal-to-noise ratio, that can be statistically planned for in establishing the link budgets.

Second, the separation between array sites will be great enough so that the Delta Differential One-Way Range (Delta-DOR) navigation data type can be used. Furthermore, this data type can be realized in real time, as opposed to the latency now incurred to transmit the data between DSN complexes.

Comparison to X-band Capability. There is not a single number that can compare the X-band and Ka-band performance of an antenna under all conditions. Even assuming operation in a vacuum, i.e., without atmospheric effects, the G/T varies differently with elevation angle at the two frequency bands. For example, assuming vacuum, the Ka-band G/T for the 34-m BWG antennas is slightly more than 7-dB above the X-band value at 45 degrees elevation, and slightly less than 7-dB above the X-band value over all elevations. Atmospheric and weather effects complicate the comparison further. As a general rule of thumb, it is typically assumed that the Ka-band G/T is 6-dB (4 times) higher than the X-band G/T. Thus the Ka-band G/T of the full 3600-antenna Array System at one longitude will be 400 times greater than the current X-band G/T of one 70-m antenna, and 500 times greater if site diversity for weather is considered.

Capacity of DSN with Array System Compared to Today

When in place at all three longitudes, the Array System will have a total Ka-band G/T of 1200 to 1500 times the X-band G/T of one 70-m antenna. Counting a new 34-m BWG antenna coming on line in late 2003, the DSN has three 70-m antennas, and nine 34-m antennas. The total X-band capacity is approximately equivalent to five 70-m antennas. Therefore, the total Array System Ka-band capacity will be 240 to 300 times today's X-band capacity.

5. Cost and Return on Investment

The biggest challenge in the Array System effort is cost. There are significant technical challenges is many areas, including antennas, microwave elements, low noise amplifiers, cryogenics, ground communications, signal processing, monitor and control, and operations and maintenance. For the most part, however, the technical performance in itself is not the main issue. The issue is how to achieve the technical performance at the lowest possible cost. The cost to be minimized is total life cycle cost, including non-recurring engineering, prototype development and testing, final system design, implementation cost, and operations, maintenance and sustaining engineering costs.

Cost Model

The costs for the Array System are not accurately known at this time. Implementation of the final system will not start until about 2009. A prototype array consisting of 100 12-m antennas is under development, with implementation and testing planned by 2008. A major objective of the prototype effort is to accurately estimate the costs for the final Array System. At this time, the cost goals are to implement the final system at a capital cost of \$10M per 70-m equivalent aperture, and to achieve operations, maintenance and sustaining costs of 5 to 7 percent per year of the capital cost to date.

Capital Cost. The capital cost includes non-recurring engineering, the prototype array, and the recurring costs. The cost goal for the recurring costs is \$9M per 70-m equivalent, or \$250K per 12-m antenna, if this is the final antenna diameter. This \$250K includes the antenna elements and a pro-rata share of other system elements. The non-antenna elements will cost between one-third and one-half of the total capital cost. This means that the 12-m antennas must be realizable at a cost of \$125K to \$165K each, including dish, subreflector, backup structure, pedestal, pointing and control system, LNA, cryogenics, and other antenna-located equipment. This cost goal will not be achieved in the prototype array, but appears to be doable for the final Array System, with further cost reductions and mass production.

Operations Cost. The operations cost, including maintenance and sustaining engineering, is a major portion of the life cycle cost, and can exceed the capital cost over the lifetime of the system. A grass-roots estimate of operations costs for the Array System has not yet been made, but will be made during the prototype effort. Meanwhile, we are estimating the annual operations cost to be 5 to 7 percent of the to-date capital cost. This is somewhat higher than the operations costs for the DSN or for the Very Large Array (VLA). A lower cost is not predicted at this time because of the large number of system elements, the geographical diversity, and many other uncertainties.

Cost and Performance Time Profiles

Figure 4 shows the estimates annual cost to complete the Array System by 2027, achieving a total increase in DSN capacity of 240 to 300 times today's capacity. A reasonable cost profile is chosen for the prototype phase through 2008, and then annual funding is ramped up to a peak level and then held constant until completion of the system. Two profiles are shown, for operations (O&M) costs of 5 and 10 percent per year of to-date capital cost. The annual cost to achieve the full array is approximately $240M if the annual operations cost is 5 percent, but increases to approximately $340M if the annual operations cost is 510 percent. This illustrates the importance of designing the system to minimize operations costs.

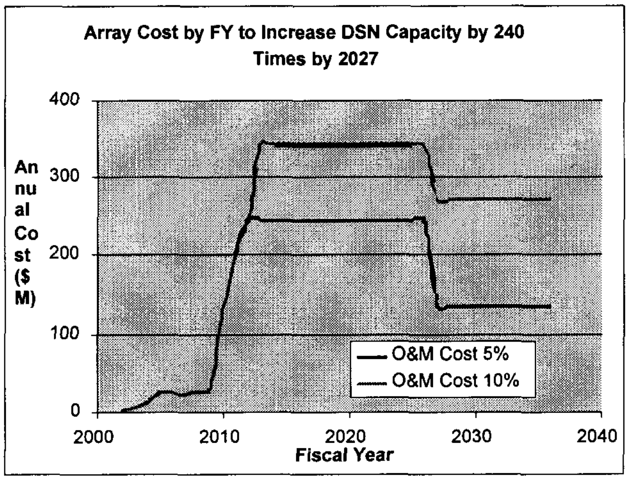

Figure 4. Annual Array Cost to Increase DSN Capacity 240 to 300 Times by 2027

Figure 5 shows the DSN capacity versus time, relative to the capacity planned for 2005. This is also shown for the two operations costs. Performance does not increase linearly with time. As the system grows, the operations cost grows. With the capped funding profile, there is less money left each year for capital spending, after paying the operations cost. Thus fewer antennas are implemented each succeeding year. The effect is somewhat more pronounced for the higher operations cost.

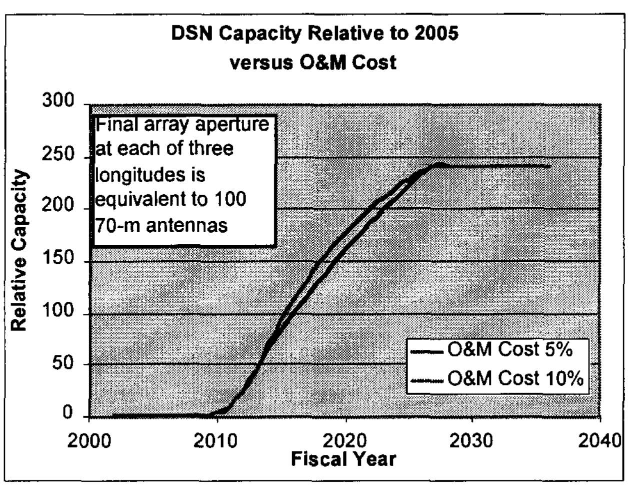

Figure 5. DSN Capacity Relative to 2005 versus Annual Operations and Maintenance Cost

Figure 5 illustrates that the DSN capacity can be increased by a factor of ten by 2012 to 2013, a factor of 100 by about 2017, and a factor of 240 to 300 by completion in 2027. This will enable the DSN to fulfill the vision of increasing capability by a factor of 10 each decade, or 1 dB per year, for the next 25 years.

Figure 6 shows the array G/T capability at each longitude compared to one 70-m antenna, versus time. The G/T at each longitude represents the increase in data rate that could be achieved for a single mission, assuming the data rate is not limited by allocated bandwidth. These curves do not include the approximate 25 percent increase in array capability due to weather diversity.

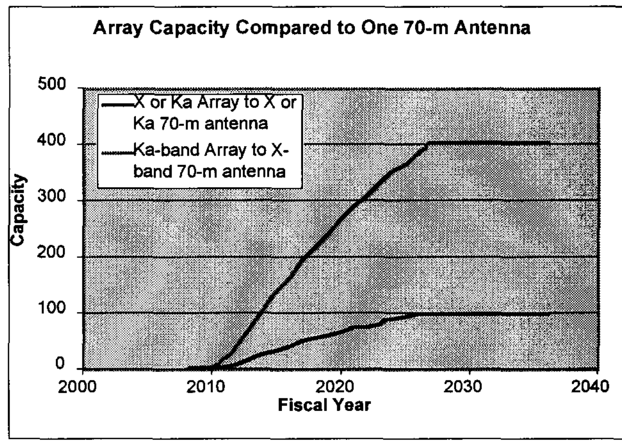

Figure 6. Array Capacity (G/T) at Each Longitude Compared to One 70-m Antenna

Return on Investment

The type of return on investment realized by the Array System is a huge increase in mission data return for a relatively modest investment, resulting in an enormous decrease in the cost per bit of returned data. The total current annual cost for the DSN is on the order of $200M. From Figure 4, and assuming that the 5 percent annual operations cost can be realized, the cost for the Array System would be approximately $250M per year in the implementation phase, and $140M per year in for operations after implementation is complete. Thus, very roughly speaking, adding the Array System to the DSN would approximately double the annual DSN cost. For this, the mission data return capability would be increased by a factor of 240 to 300. Thus the cost per data bit is reduced by a factor of more than 100.

It is noted that less expensive options are also possible. The array performance is closely proportional to the number of antennas in the system, and is therefore approximately proportional to cost, provided that a large enough array is implemented so that non-recurring costs do not dominate. For example, suppose that the annual cost is capped at $100M, thereby increasing the annual DSN budget to 1.5 times today's budget. This would be sufficient to realize a total system capacity of 100 to 125 times today's capacity. The cost per mission data bit returned would be reduced by a factor of approximately 67 to 83.

6. CONCLUSIONS

Very large arrays are a promising way to achieve the deep space mission science data return that is projected to be needed in the next 10 to 25 years. This greatly increased data return will enable the missions to get much more science per mission. As a simple example, a Mars mapping mission could return high-resolution maps of the entire planet, instead of the 1 to 5 percent of the surface to be mapped by the Mars Reconnaissance Orbiter (MOR). The Array System will also enable new mission concepts using smaller a lighter spacecraft, new instruments such as for high-resolution multi-spectral imaging, and high data rate from Saturn, Pluto and beyond. At the same time, the Array System will reduce the cost per bit of science data return by more than 100 times.

ACKNOWLEDGEMENTS

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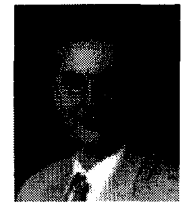

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